

First TOPSAR image and interferometry results with TerraSAR-X

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ABSTRACT

TOPSAR is a recently proposed SAR mode for wide swath acquisition, which is foreseen to be used by the ESA Sentinel-1 SAR sensor in its main interferometric wide swath mode. The Microwaves and Radar Institute of the German Aerospace Center is validating TOPSAR mode in space with TerraSAR-X data within the framework of an ESA commissioned project. Several TOPSAR images have been successfully commanded, acquired and processed. First TOPSAR images are presented. A pair of TOPSAR data takes over a high coherent area (the Uyuni salt lake in Bolivia which has already shown good phase stability with 11 days repeat pass TerraSAR-X acquisitions) has been acquired and preliminary interferometric results are presented in the paper. Coregistration accuracy requirements are discussed.

1. INTRODUCTION

Large swath coverage is an essential requirement for a number of applications. The standard ScanSAR mode achieves this requirement by periodically switching the antenna elevation beam to point at different range subswaths [1], [2], hence acquiring a certain number of bursts per subswath. The trade-off is the azimuth resolution loss due to the reduction of the observation time of targets.

However, the ScanSAR mode has some disadvantages besides resolution loss: scalloping (periodical modulation of the amplitude in the focused image), and azimuth-varying ambiguity ratio and noise equivalent sigma-zero. They are a consequence of the fact that different targets are observed under different portions of the azimuth antenna pattern. In order to reduce these effects, different bursts are incoherently averaged, with the consequent further worsening of the azimuth resolution.

A new wide swath imaging mode, TOPS (Terrain Observation by Progressive Scans), has been proposed by Attema (ESA-ESTEC) and Rocca (POLIMI) and successively developed in [3]. It overcomes the problems of scalloping and azimuth-varying ambiguities introduced by the conventional ScanSAR mode by means of steering the antenna along-track. The solution proposed in [3] to achieve the same swath coverage and

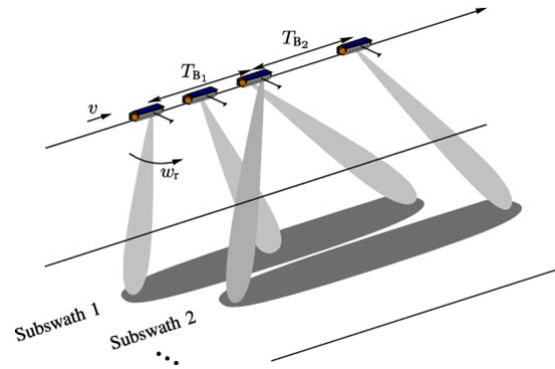


Figure 1. Acquisition geometry of the TOPSAR imaging mode.

avoid the undesired effects of ScanSAR consists in rotating the antenna throughout the acquisition from backward to forward at a constant rotation speed (see Fig. 1), opposite to the spotlight case, resulting in the opposite effect, i.e. a worsening of the azimuth resolution. However, all targets are observed under the same azimuth antenna pattern, and therefore the scalloping effect is drastically reduced and distributed target ambiguities noise ratio (DTAR) and signal-to-noise ratio (SNR) become nearly constant in azimuth.

TerraSAR-X is able to electronically steer the antenna azimuth pattern. This capability offers the opportunity to implement on the satellite the recently developed TOPSAR acquisition mode.

In the following Section 2, TOPSAR and inverse TOPSAR acquisition modes are briefly illustrated. Successively, first TOPSAR images acquired with TerraSAR-X and processed with the experimental processor developed at DLR [4] are presented and discussed in Section 3. Section 4 describes the accuracy coregistration requirements both in range and in azimuth for TOPSAR interferometry. Very first TOPSAR interferometric results are shown in Section 5: a pair of TerraSAR-X TOPSAR data takes acquired over the high coherent region of the Uyuni salt lake in Bolivia have been acquired and processed. Finally, conclusions and future work are addressed in Section 6.

2. TOPSAR AND INVERSE TOPSAR

The basic principle of TOPSAR is the shrinking of the antenna pattern obtained by steering the antenna in the opposite direction as for Spotlight.

For the resolution, SNR and DTAR performance, the driving parameter is the shrinking factor [3]. However, since the antenna gain is symmetric the same antenna shrinking can be obtained steering the antenna in the same direction as in Spotlight, with a steering angle rate which is higher than the nominal TOPSAR because it has to compensate also the platform movement. Both TOPSAR and inverse TOPSAR have the same burst length for a given resolution and integration beamwidth [5], therefore in inverse TOPSAR larger steering angles are required which results in an increased scalloping effect when compared with nominal TOPSAR mode. It is important to note that the TOPSAR scalloping effect is induced by the reduced gain of the main lobe for squinted angle (see Fig. 2) in array antenna systems and that this value is much smaller than in ScanSAR. Typical values for TerraSAR-X are reported in Fig. 3.

Residual TOPSAR scalloping can be removed with conventional techniques, and being TOPSAR burst much longer than ScanSAR effect its removal is less sensible to inaccuracy of Doppler centroid knowledge. In order to have TOPSAR raw data scalloping free, an increased number of transmitting modules are required in the antenna array, given a certain total antenna length. This aspect should be an element to take into account in the design of future spaceborne SAR payload.

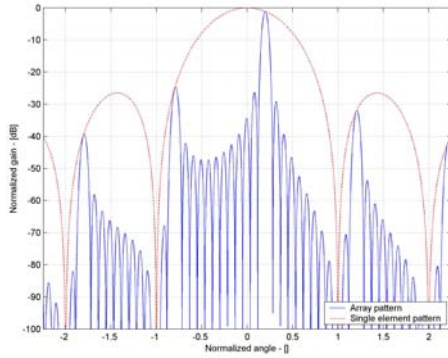


Figure 2. Single element pattern and array antenna pattern for a pointing angle corresponding to a normalized angle of 0.2. The array antenna pattern is amplitude weighted by the single element pattern and grating lobes are present.

3. FIRST TOPSAR IMAGES

An experimental phase preserving TOPSAR processor has been developed at DLR-HR [4] and it has been used for the processing of the images shown in this paper. The first inverse TOPSAR data take has been acquired by TerraSAR-X on June 29th, 2007, only two weeks after the satellite launch and is reported in Fig. 4a. The SAR image represents a scene over Vendome, France. The scene size is approximately 84 km in azimuth and 72 km in slant range direction. In all the pictures shown in this paper, slant range is on horizontal direction, azimuth on the vertical direction.

The commanded steering angle is between plus and minus 0.71 degree. However, during the commanding a burst overlap has been introduced as safety margin, therefore the burst image without overlap has been acquired with an azimuth steering angle variation of plus minus 0.67 degree. A small scalloping effect is visible in the inverse TOPSAR image. No weighting has been applied in the overlapping region nor has scalloping correction been performed; therefore the picture shown is the “real” TOPSAR image. An azimuth profile has been extracted from three bursts showing a homogeneous area and is plotted in Fig. 4b. A variation of approximately 0.7 dB can be seen in the azimuth profile and this value corresponds very well to the expected performance.

A nominal TOPSAR image is shown in Fig. 5a. It has been acquired over Toulouse, France. The scene size is approximately 90 km in azimuth and 75 km in slant range. The TOPSAR data take has been generated in order to have the same azimuth resolution as the

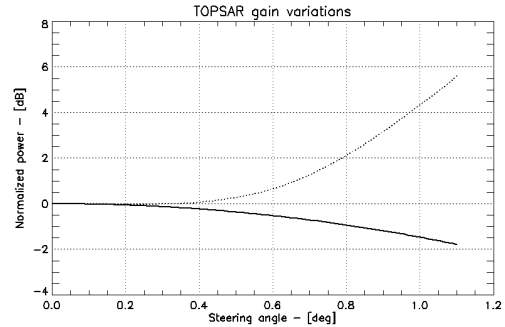


Figure 3. TOPSAR main lobe (solid line) and azimuth ambiguity power (dotted line) variation depending on the steering angle for a typical TerraSAR-X configuration example. The power variation is normalized to the boresight case.

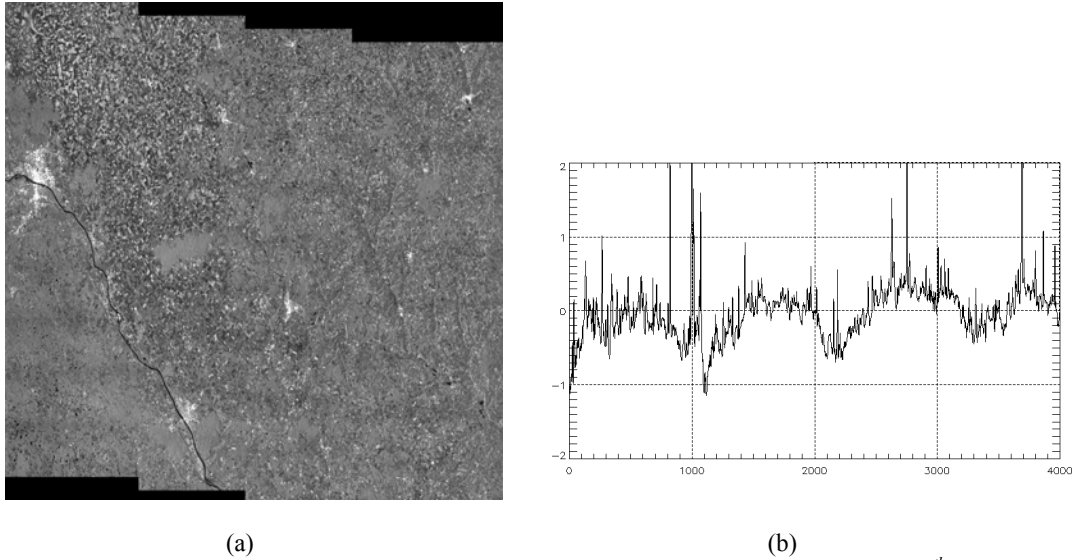


Figure 4. The first inverse TOPSAR data take has been acquired by TerraSAR-X on June 29th, 2007, only two weeks after the satellite launch and is reported in (a). The SAR image represents a scene over Vendome, France. The scene size is approximately 84 km in azimuth and 72 km in slant range direction. An azimuth profile has been extracted from three bursts showing a homogeneous area and is plotted in (b). A variation of approximately 0.7 dB can be seen in the azimuth profile and this value corresponds very well to the expected performance.

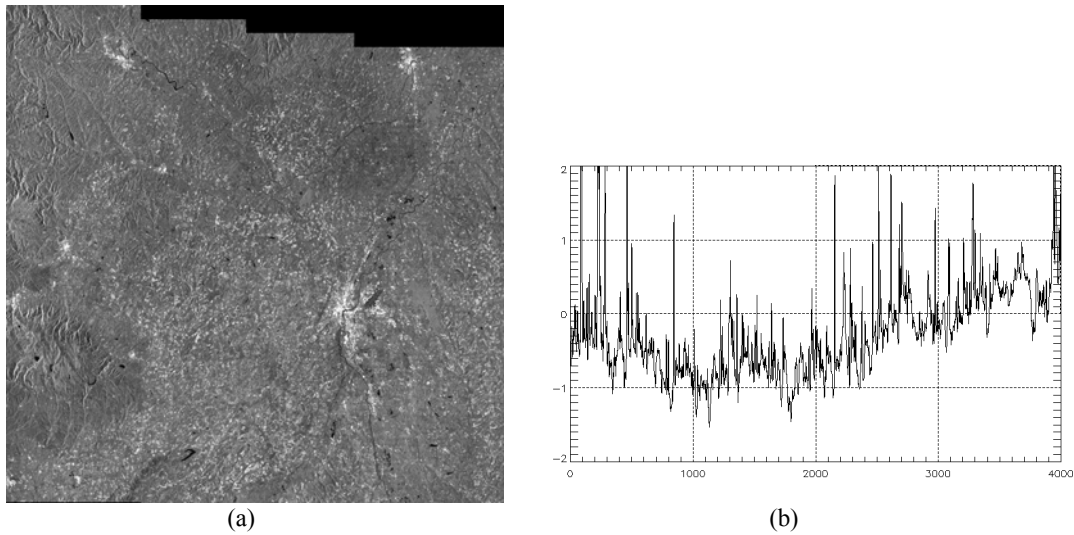
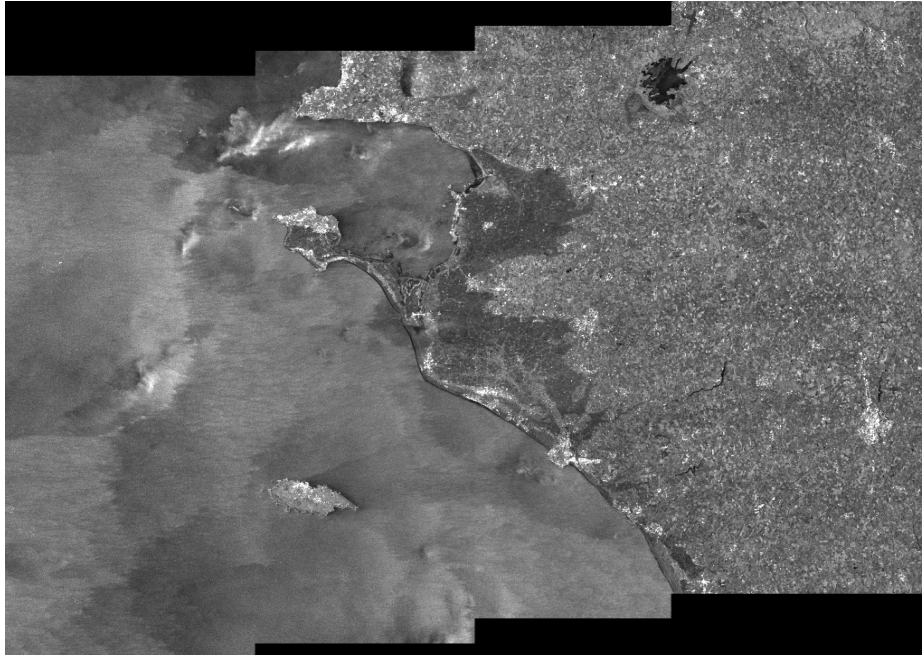


Figure 5. A nominal TOPSAR image is shown in (a). It has been acquired over Toulouse, France. The scene size is approximately 90 km in azimuth and 75 km in slant range. Due to the low variation of the burst image steering angle (within plus/minus 0.44 degree), scalloping is hardly visible. An azimuth profile has been extracted from three bursts showing a homogeneous area and is plotted in (b).



(a)



(b)

Figure 6. A TOPSAR data take over Challans, France, has been executed on July 9th, 2007 and is shown in (a). Slant range is on horizontal direction, azimuth on the vertical direction. For comparison, a TerraSAR-X ScanSAR data take has been acquired over the same area and with the same geometric configuration on September 2nd, 2007 and it is shown in (b). All radiometric correction steps have been performed in the ScanSAR image, including scalloping correction. However, while the land area is scalloping free, the presence of scalloping is clearly observable in the ocean area, where the burst edges are easily identified. Indeed, in low signal to noise ratio area, noise is amplified at the burst edges when scalloping correction is applied. Different color scaling patterns have been used for the two pictures.

Vendome one, previously described. The commanded steering angle is between plus and minus 0.55 degree and a burst image without overlap has been acquired with an azimuth steering angle variation of plus minus 0.44 degree. Also this picture is showing the “real” TOPSAR image discarding the burst overlapping regions and without scalloping correction. Due to the lower variation of the steering angle, the scalloping effect is hardly visible and it has been quantified to approximately 0.4 dB from the azimuth profile shown in Fig. 5b. Therefore, as shown from this comparison and as expected from theoretical evaluations [5], TOPSAR mode is always preferable to inverse TOPSAR mode in systems with electronic steering array antennas.

A TOPSAR data take over Challans, France, has been executed on July 9th, 2007. The data acquisition has been planned with four subswaths, and six bursts for each subswath. The azimuth antenna pattern has been steered from -0.5 degree to +0.5 degree. Each burst image has an extension of approximately 12 km in the along-track direction. The TOPSAR processed image is shown in Fig. 6a. Incident angle is varying from 21 to 30 degree. The scene extension is approximately 100 km in range and 85 km in azimuth.

For comparison, a TerraSAR-X ScanSAR data take has been acquired over the same area and with the same geometric configuration on September 2nd, 2007. The presented image has been generated by the TerraSAR-X operational processor, which implements all the radiometric correction steps, including scalloping correction. However, while the land area is scalloping free, the presence of scalloping is clearly observable in the ocean area, where the burst edges are easily identified. Indeed, in low signal to noise ratio areas, noise is amplified at the burst edges when scalloping correction is applied.

The presence of two little islands in the bay is not observable in the ScanSAR image when compared with the previously shown TOPSAR image. By verifying the tide level in the two acquisition days, it was confirmed a difference of more than 3 meters in the tide level at the time of the two acquisitions.

4. COREGISTRATION ACCURACY IN TOPSAR INTERFEROMETRY

One of the characteristic of a TOPSAR mode is that data are acquired with high Doppler centroid variations. For typical TerraSAR-X TOPSAR acquisitions, the Doppler centroid can vary as much as more than 10 kHz. It is well known that in presence of squint, linear phase ramps are induced in the focused response both in azimuth and in range direction [6]. Therefore, slight misregistration can cause the presence of phase bias.

4.1. Range coregistration accuracy

The expression for the interferometric phase error induced by a linear ramp of the impulse response in range direction when range misregistration is present is [6]:

$$\varphi_{rg_err} = \frac{4\pi}{\lambda} \Delta r_{mis} \left(1 - \sqrt{1 - \left(\frac{\lambda f_{DC}(r_0)}{2v} \right)^2} \right) \quad (1)$$

This expression results in very negligible values, therefore TOPSAR does not introduce any additional stringent requirement for range coregistration accuracy in interferometry applications.

4.2. Azimuth coregistration accuracy

Since each TOPSAR burst is acquired with a varying Doppler Centroid every focused point presents a different linear phase ramp in the azimuth direction. The slope of the ramp depends on the Doppler centroid. The resulting interferometric TOPSAR phase bias in the presence of azimuth misregistration is similar to the ScanSAR bias and it is equal to [7]:

$$\varphi_{az_err} = 2\pi f_{DC} \Delta t \quad (2)$$

Within a burst, this corresponds to a linear phase term, since f_{DC} is a function of the azimuth position within the

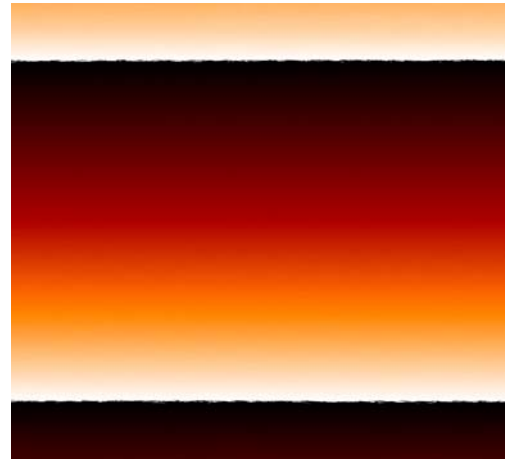


Figure 7. Resulting interferogram obtained by using a TerraSAR-X TOPSAR burst and an azimuth shifted replica of the same burst. The applied shift is 0.1 of the pixel and the resulting phase ramp is as expected

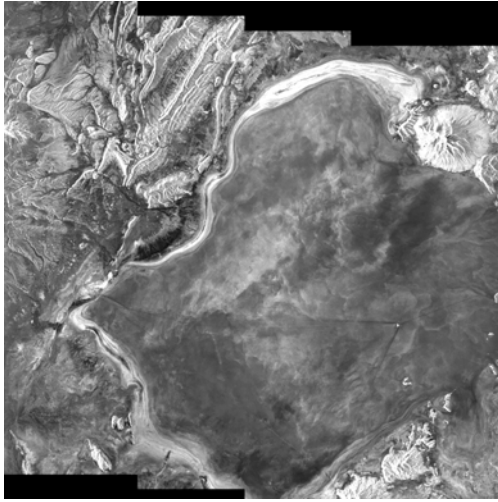


Figure 8. The TOPSAR amplitude image used as master for the interferometric analysis. The data take has been acquired by TerraSAR-X on October 10th 2007 over the Uyuni salt lake, Bolivia, one of the largest in the world. In the middle of the salt lake is possible to see a little island and the paths left by the vehicles used to reach the island.

burst. For a TerraSAR-X acquisition with Doppler variation of 10.35 kHz, pixel spacing of 8.69 meter, a misregistration of 0.1 pixel spacing introduces a ramp of approximately 2.5π within the burst. Therefore, an azimuth coregistration accuracy of better than 0.01 pixel spacing would be required for this configuration acquisition.

In order to visualize the effect of azimuth misregistration, Fig. 7 shows the resulting interferogram obtained by using a burst and an azimuth shifted replica of the same burst. The applied shift is 0.1 of the pixel and the resulting phase ramp is as expected from (2).

The required coregistration accuracy could be achieved by performing a pixel coregistration using orbit's information or amplitude cross-correlation, then a fine coregistration using spectral diversity [7] within the burst; finally very fine coregistration accuracy can be obtained by using again spectral diversity techniques on the overlapping region of two consecutive TOPSAR bursts.

5. PRELIMINARY TOPSAR INTERFEROMETRY RESULTS

Several TOPSAR data takes are currently being acquired over a flat and high coherent region. The chosen area is the Uyuni salt lake, Bolivia, one of the

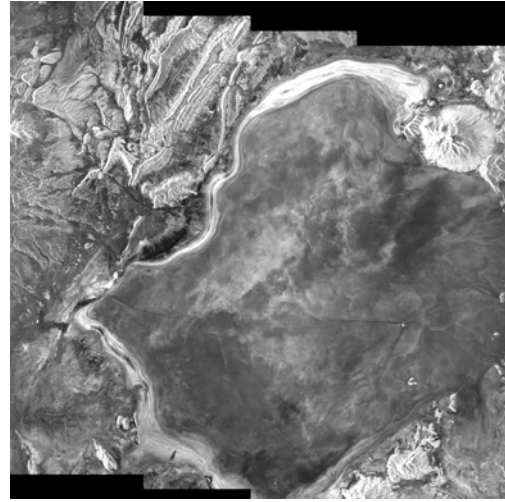


Figure 9. Slave amplitude TOPSAR image used for the interferometric analysis. The data take has been acquired by TerraSAR-X on October 21st 2007

largest in the world. The first two TOPSAR data take have been acquired by TerraSAR-X on October 10th 2007 and October 21st 2007 and have been used for a preliminary TOPSAR interferogram analysis.

The master and the slave TOPSAR image are shown in Fig. 8 and Fig. 9. The data have been acquired with four subswaths and 8 bursts. Look angle is varying from 32.9 degree to 37.9 degree. The slant range swath is 74 km while the scene azimuth extension is 110 km. Pixel

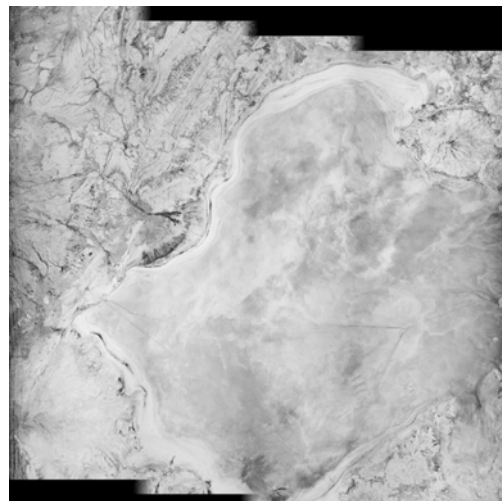


Figure 10. Coherence image of the Uyuni TOPSAR interferometry analysis

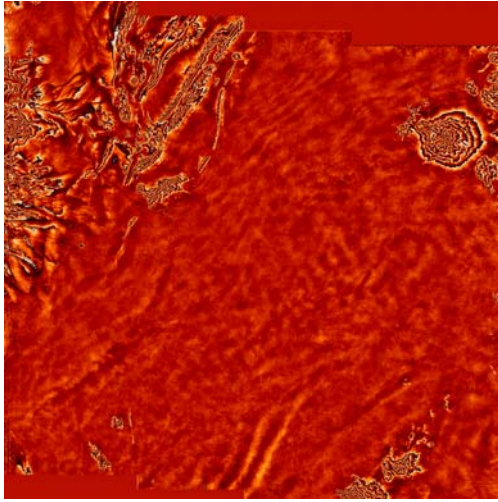


Figure 11. Final TOPSAR flattened interferogram. Topographic fringes are clearly visible over the mountainous areas

spacing is 8.69 m. Around the salt lake it is possible to see mountainous areas whereas a small island is visible within the lake.

For the preliminary TOPSAR interferometry analysis reported in this paper, each burst has been coregistered with an accuracy of 0.1 pixel spacing by coherence maximization techniques. The mean of the estimated along track shift between the two acquisition is around 20 meter, which allows good TOPSAR spectrum burst overlap. By using this information, the slave TOPSAR image has been reprocessed in order to maximize Doppler spectrum overlap and reduce azimuth fringe induced by the azimuth misregistration.

The resulting coherence picture is shown in Fig. 10. Variation of coherence is noticeable at the range subswath edge due to the variation of the antenna elevation gain. The same effect would be present also in ScanSAR coherence data takes.

For the phase earth removal, both range and azimuth fringe frequency has been estimated for each interferogram burst and a linear fit has been performed for the complete interferogram. The final interferogram is shown in Fig. 11.

The estimated range frequency is linearly decreasing with increasing range and with along-track position, resulting in an estimated perpendicular baseline varying from 67 to 38 meter. The resulting ambiguity height is varying from approximately 92 to 173 meter.

6. CONCLUSIONS AND FUTURE WORK

First TOPSAR images acquired with TerraSAR-X have been presented. The data have been processed with the experimental processor developed at DLR. Nominal TOPSAR and inverse TOPSAR images have been produced. Residual scalloping is visible and is approximately 0.4 dB in typical TerraSAR-X TOPSAR acquisitions.

Requirements for TOPSAR interferometry coregistration accuracy have been analyzed. Preliminary TOPSAR interferometry results have been presented by processing two images acquired over a flat and high coherent area.

Future works include a quantitative analysis of the interferogram, the processing of other TOPSAR data takes acquired over the same area and comparison with ScanSAR interferometry results over the same area.

The final outcomes of this research will be used as suggestions for the implementation of the Sentinel-1 TOPSAR Interferometric Wide Swath mode.

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